ELSEVIER
Aquaculture 158 (1997) 57–67
Aquaculture

Ozonation of a recirculating rainbow trout culture system [1]
II. Effects on microscreen filtration and water quality

Steven T. Summerfelt *, Joseph A. Hankins, Amy L. Weber, Martin D. Durant

The Conservation Fund's Freshwater Institute, P.O. Box 1746, Shepherdstown, WV 25443, USA

Accepted 23 February 1997

Abstract

Ozone was added to water in a recirculating rainbow trout (*Oncorhynchus mykiss*) culture system just prior to the culture tanks in order to oxidize nitrite and organic material, improve overall water quality, and assist removal of solids across the microscreen filter. Data from four 8-week studies on ozonation and an 8-week no ozone control indicated that adding ozone reduced the mean concentration of TSS by 35%, COD by 36%, DOC by 17%, and color by 82% within the water entering the culture tanks. Additionally, ozone reduced the mean nitrite concentration by 82% within the culture tanks. Adding ozone did not affect turbidity. Changes brought on by ozonation, particularly as it affected the characteristics of the suspended solids, also improved suspended solids removal across the Triangel™ filter by an average of 33%. In addition, adding ozone decreased plugging of the microscreen filter panels, as indicated by an average of 35% fewer filter wash cycles, 53% less filter sludge flow produced, and 79% more settled solids volume in the Triangel™ filter effluents. Comparison of two different ozone dosing rates indicated that adding ozone to our recirculating system at a rate of 0.025 kg ozone per kilogram feed was

* Corresponding author.

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PII S0044-8486(97)00064-1

nearly as effective as adding ozone at a rate of 0.036–0.039 kg ozone per kilogram feed.

Keywords: Ozone; Recirculating system; Solids removal; Microscreen filtration; Water quality

1. Introduction

Microscreen filters are used to minimize the accumulation of solids within recirculated aquaculture systems. However, dissolved and colloidal organic matter are not readily removed by microscreen filters (Summerfelt et al., 1994) or by most conventional clarification techniques (Chen et al., 1994). If the organic matter is not removed, it can exert an unwanted oxygen demand, inhibit nitrification, and harbor opportunistic pathogens within the recirculated systems (Chen et al., 1994). Methods or processes that improve solids removal can improve water quality and, potentially, enhance production and reduce certain operating costs. Ozone can precipitate dissolved organic molecules and microflocculate colloidal organic solids (Maier, 1984) and, thus, enhance the removal of organic materials from process flow streams via sedimentation, flotation, or filtration.

Ozone is particularly well suited to aquaculture applications because it has a wide range of oxidizing uses, a rapid reaction rate, few harmful reaction by-products in freshwater, and oxygen production is an end product of reaction. Since many contaminants in aquaculture waters are oxidizable, ozone can be used in applications ranging from disinfection to general water quality control. Ozone has traditionally been used to sterilize water supplies and/or discharges of aquaculture systems. However, ozone has also been used within recirculating aquaculture systems (Otte et al., 1977; Otte and Rosenthal, 1979; Rosenthal and Otte, 1980; Rosenthal, 1981; Williams et al., 1982; Sutterlin et al., 1984; Rosenthal and Kruner, 1985; Paller and Lewis, 1988; Poston and Williams, 1988; Reid and Arnold, 1992; Bullock et al., 1997). The literature indicates that ozonation provides recirculating systems with benefits other than disinfection through supportive water treatment that can include color removal, oxidation of nitrite and non-biodegradable organic matter (subsequently making them degradable by bacteria), and improved suspended solids removal by flotation and clarification.

Much of the research reported on ozone's affects on water quality was conducted within brackish water systems and with ozone added in a batch manner outside of the main recirculating water loop, which make their results less useful to freshwater users and users that plan to apply ozone continually to the entire recirculated flow. Also, previous research neither described ozone's effect on microscreen filter performance, nor provided criteria that could be used to relate the amount of ozone required with respect to the daily fish feed input. Research by Wilczak et al. (1992) and Rueter and Johnson (1995) showed that ozonation improved solids removal through sedimentation and granular filtration, and research by Sander and Rosenthal (1975), Otte and Rosenthal (1979), and Williams et al. (1982) showed that ozonation improved removal of organic material through foam fractionation. Depending upon the particles surface properties, ozone can affect particulates differently. In some cases, ozonation can increase particle stability and decrease microflocculation (Maier, 1984; Grasso and Weber, 1988; Edwards and Benjamin, 1991; Wilczak et al., 1992). Therefore, it was clear that research was needed to determine how continuous ozonation of the recirculating water affects microscreen filtration and water quality within freshwater systems.

In this research, our objectives were to demonstrate ozone's affect on water quality and microscreen filtration when ozone was added at levels that could be obtained by creating 3–4% ozone within the existing oxygen feed gas. The oxygen feed gas would thus serve to both introduce ozone and to provide a dissolved oxygen supersaturation within each culture tank's influent. An accompanying paper by Bullock et al. (1997) describes the effects of moderate levels of ozone on bacterial gill disease (BGD) epizootics and numbers of heterotrophic bacteria.

2. Materials and methods

The recirculating system consisted of two cross-flow fish culture tanks, two multi-stage low-head oxygenators (LHO™), [2] two microscreen filters, one fluidized-sand biofilter, and one cascade aeration column. Water was recirculated in two parallel flow paths (a path for fish culture and a path for biofiltration and carbon dioxide stripping) connected within a common sump as described by Heinen et al. (1996). Rainbow trout were reared using a continuous culture strategy as described by Summerfelt et al. (1993). A biomass of about 2000 kg was averaged within each 9.0 m^3 culture tank during these studies. Ozonation of the recirculating system was studied through four 8-week tests and an 8-week no ozone control. Approximately 0.025 and 0.036–0.039 kg ozone were added per kilogram feed fed in the first two ozone tests and the last two ozone tests, respectively. A more detailed description of the ozone tests, recirculating system design, method of ozone addition, and fish and feeding practice used are provided in the companion paper by Bullock et al. (1997).

2.1. Microscreen filter evaluation

Microscreen filters remove water-bound particles that are too large to pass through the openings in their screen panels. Experiments were designed to evaluate the performance of the Triangel™, filter when ozone was or was not added to the system. The Triangel™ filters evaluated (Model TF-12-RB; Hydrotech, Villinge, Sweden) used 80-μm opening sieve panels to each treat 360 l/min. Triangel™ filters operate by distributing flow in a thin layer across a weir and onto one side of a flat sieve panel (Fig. 1). Water drips through the sieve and particulates larger than the openings are left behind. As particulates accumulate on the sieve, water level on the sieve panel increases fractionally, and provides the motive force for the flow to travel further down the panel. The flow across the top of the panel pushes a thin barrier of accumulated particulates

[2] Use of trade name does not imply endorsement.

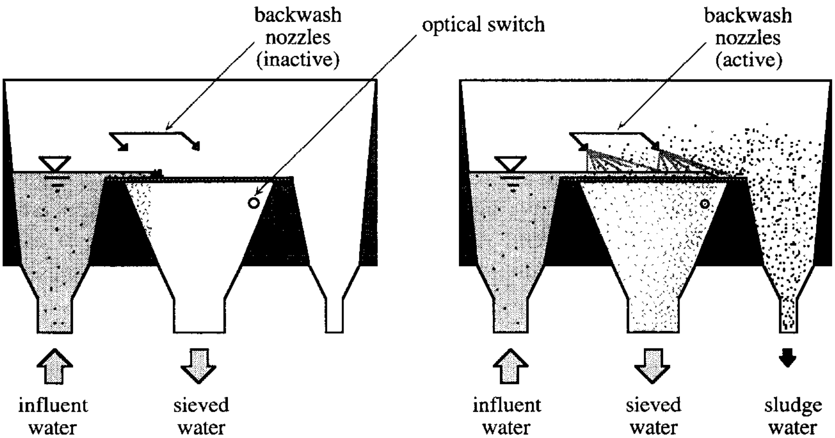

Fig. 1. Illustration of the Triangel™ filter's working mechanism. Water passes through the sieve panel while filterable solids are removed. At a certain point, the water dripping through the sieve activates an optical switch which turns on the backwash mechanism that clear solids from the sieve and washes them into a collection trough.

towards the sludge water drain (Fig. 1). Just before the flow reaches the end of the sieve panel, an optical sensor located under the sieve panel detects water falling through the screen. The optical sensor is linked to a mechanically driven high-pressure backwash which washes the accumulated solids into a sludge collection trough located at the end of the sieve panel.

During each 8-week trial, each Triangel™ filter's influent and effluent total suspended solids (TSS) concentrations were measured once a week, beginning after the first week. Total daily solids removal across each filter was calculated from the difference between the influent and effluent TSS concentrations multiplied by the flow to each filter.

Sludge production rate, sludge settled solids volume, and number of wash cycles were measured weekly by capturing 10 to 20 l of Triangel™ filter sludge effluent. Daily sludge water production and number of daily wash cycles were determined by extrapolating the results of the sampling period over the entire day.

2.2. Determination of water quality

Concentrations of TSS, chemical oxygen demand (COD), total organic carbon (TOC), dissolved organic carbon (DOC), nitrite, water color, and turbidity were measured in the recirculated water before and after each LHO™ when ozone was added, before and after each two culture tank, and after each microscreen filter. No samples were taken during the first week of each 8-week trial to allow the system to stabilize. During each trial, TSS, COD, and DOC were measured once weekly, for at least six of the remaining seven weeks, while color, nitrite, and turbidity were measured three times a week each trial. COD concentrations were measured using test procedures, COD2 reagents, COD Reactor, and DR2000 or DR3000 spectrophotometers from Hach Chemical (Loveland, CO). Nitrite concentrations were measured using the diazotization method and Hach Chemical reagents and either a DR2000 or DR3000 spectrophotometer. TSS concentrations were measured using APHA (1985) method 209 C. Color samples were filtered through 0.5-μm filter paper before being analyzed based upon a Pt–Co standard using APHA (1985) method 204 B and a Hach Chemical DR2000 or DR3000 spectrophotometer at 455 nm wavelength. Turbidity was measured with a Hach Chemical Ratio/XR turbidimeter using APHA (1985) method 214 A. DOC samples were filtered through 0.5-μm filter paper before being frozen and shipped to Lancaster Laboratory (Lancaster, PA) where they were analyzed using a persulfate digestion/infrared detection method on an acidified sample which had been purged of carbon dioxide using nitrogen. Methods used to measure dissolved ozone were described by Bullock et al. (1997).

3. Results

3.1. Water quality

The sample location within the recirculating system that best showed the fullest extent of water quality treatment is used here to discuss how ozone affected water quality. The location immediately following the LHO™ (just before entering the fish culture tank) showed the lowest concentration in TSS, COD, DOC, color, and turbidity, and is used here to compare the effect of ozone on water quality. Ozone reduced nitrite to the lowest levels within the fish culture tanks, so the concentration data measured in the first culture tank (C-1) was used to compare nitrite reductions between trials (Table 1).

Ozone reduced the accumulation of suspended particulates, dissolved organics, water color, and nitrite in all trials with respect to the control (Table 1): TSS entering C-1 was reduced from an average of 6.3 mg/l in the control to 2.9–5.6 mg/l; COD entering C-1 was reduced from an average of 43.6 mg/l in the control to 23.8–36.7 mg/l; DOC entering C-1 was reduced from an average of 7.1 mg/l in the control to 5.5–6.3 mg/l; color in the water entering C-1 was reduced from an average of 17.7 Pt–Co units in the

Table 1
Mean (±s.e.) total suspended solids (TSS), chemical oxygen demand (COD), dissolved organic carbon (DOC), color, and turbidity in the culture tank influent and nitrite within the culture tank water during each ozone treatment

Treatment	Ozone dose (kg/d)	TSS (mg/l)	COD (mg/l)	DOC (mg/l)	Color (Pt-Co)	Turbidity (NTU)	Nitrite (μg/l)
Control	0.0	6.3±1.1	43.6±3.8	7.1±0.4	17.7±1.2	1.58±0.08	265±15
1	0.68	4.0±0.6	26.1±1.5	NA	5.3±0.9	1.49±0.14	50±12
2	0.68	2.9±0.6	25.7±5.6	6.3±0.3	2.9±0.4	0.94±0.05	24±6
3	1.0 to 1.3	5.6±0.4	36.7±5.5	6.0±0.3	2.1±0.5	2.02±0.16	73±18
4	1.0 to 1.3	3.9±1.0	23.8±1.4	5.5±0.2	2.0±0.5	1.13±0.06	46±20

Table 2
Mean (± s.e.) Triangel™ filter performance during the control and each ozone trial

Treatment	Sludge water produced (l/d)	Settled solids volume of sludge produced (ml/l)	Filter wash frequency (no./day)	Solids removed across filter (kg/d)	Mean daily dry[a] feed rate (kg/d)	Fraction of dry weight feed removed (kg/kg)
Control	4090 ± 520	20.6 ± 2.3	3080 ± 290	3.4 ± 0.4	14.1	0.24
Trial 1	2520 ± 280	31.5 ± 2.3	2420 ± 120	4.5 ± 0.9	13.3	0.33
Trial 2	2090 ± 180	34.1 ± 1.9	2230 ± 100	4.5 ± 0.6	13.2	0.34
Trial 3	1610 ± 120	38.3 ± 1.4	1760 ± 70	4.1 ± 0.4	11.8	0.35
Trial 4	1470 ± 160	43.2 ± 2.1	1610 ± 50	3.8 ± 0.9	12.8	0.29

[a]Dry weight calculated from total weight based on 10% feed moisture content.

control to 2.0–5.3 Pt–Co units; Likewise, nitrite within C-1 was much lower during the ozone trials (means 24–73 μg/l) when compared to the control (265 μg/l).

There were no clear trends in mean turbidity between the control (1.58 NTU) and the ozone trials (0.94–2.02 NTU).

3.2. *Microscreen filter evaluation*

Adding ozone to the recirculating system greatly improved the performance of the Triangel™ filter (Table 2). Ozonation increased the removal of suspended solids across each Triangel™ filter from a mean of 3.4 kg/d in the control to 3.8–4.5 kg/d during the ozone trials. More importantly, based upon the daily feeding rate (Table 2), a larger fraction of the solids fed to the fish were removed when the system was ozonated (0.29–0.35 kg solids removed per kilogram dry feed fed) than when it was not (0.24 kg solids removed per kilogram dry feed fed). Additionally, adding ozone to the system: (1) reduced daily production of Triangel™ filter sludge from a mean of 4090 l/d in the control to 1470–2520 l/d in the four ozone trials; (2) increased the settled solids volume of the Triangel™ filter sludge effluent from a mean of 20.6 ml/l in the control to 31.5–43.2 ml/l in the four ozone trials; and (3) reduced Triangel™ filter wash requirements from a mean of 3080 cycles/d in the control to 1610–2420 cycles/d in the four ozone trials.

4. Discussion

Adding ozone to the recirculating system resulted in an overall improvement in water quality due to more complete oxidation of nitrite, color, organic material, and suspended solids. Ozone reduced the concentration of suspended particulates, dissolved organics, water color, and nitrite in all trials when compared to the control (Table 1). Over all trials, ozonation reduced the mean concentration of TSS by 35%, COD by 36%, DOC by 17%, and color by 82% within the water entering C-1. Additionally, ozonation reduced the mean nitrite concentration by 82% within C-1. Ozone did not consistently change turbidity. Changes resulting from ozonation, particularly as it affected the filterability of the suspended solids, also improved the performance of the Triangel™ microscreen filters (Table 2).

4.1. TSS and COD

The accumulation of solids and oxygen consuming compounds in recirculating systems is dependent upon the rate of feeding, the rate that solids are removed across the filter unit, and the rate that they are entrained out of the system during water exchange (Liao and Mayo, 1972). Reduction in the accumulation of TSS and COD were likely due to improved filtration resulting from ozone-induced microflocculation, as discussed in the improvements in microflocculation section (below). Although the two ozone doses evaluated within this study did show excellent reduction in TSS and COD concentrations, the higher ozone dosing rate (0.036–0.039 kg ozone per kilogram feed) did not reduce TSS or COD concentrations beyond those achieved by the lower dosing rate (0.025 kg ozone per kilogram feed).

TSS and COD that accumulated within the system were those solids and organics that could not be removed by passage through the 80-μm microscreen panel, even with the oxidative assistance provided by ozone. In an earlier study, we determined that the TSS that were not removed across the 80-μm microscreen panel were colloids that could not be removed by a screen filter with openings ≥ 40 μm (Heinen et al., 1996).

4.2. DOC and color

Non-biodegradable organic compounds accumulate in recirculating systems (Otte et al., 1977; Rosenthal and Otte, 1980; Hirayama et al., 1988). Ozone has been reported to effectively decrease the accumulation of non-biodegradable organic compounds in recirculating systems (Rosenthal and Otte, 1980). Ozone and its reaction by products are capable of oxidizing a great many organic substances (Rice et al., 1981; Bablon et al., 1991). Ozone oxidation removes color and makes organic molecules more biodegradable.

We found that ozonation greatly reduced color but only slightly reduced DOC levels (Table 1). However, color and DOC reductions at the higher dosing rate were similar to the reductions made at the lower ozone dosing rate. Reduction in the accumulation of color and DOC levels were likely due to a combination of oxidation, enhanced biodegradation, increased precipitation, and adsorption onto particulates.

Otte and Rosenthal (1979) reported that color removal was improved by ozone-enhanced foam fractionation and biofiltration in a recirculating system used to culture tilapia and European eels. Sutterlin et al. (1984) found that ozone assisted with color removal within a recirculating system that produced Atlantic salmon smolts. Rosenthal and Kruner (1985) used a synthetic fish water containing ammonia, nitrite, and peptone to show that high levels of ozone can be used to oxidize BOD, but that it required > 10 g ozone to oxidize 1 g BOD. Under normal conditions, Rosenthal and Otte (1980) reported that ozonation did not substantially affect the overall BOD within recirculating fish culture systems.

Reaction with ozone can occur directly or through an ozone decomposition product. Organic matter in recirculating aquaculture water tends to destabilize ozone; alkalinity, on the other hand, can prevent the destabilization of ozone (Staehelin and Hoigne, 1985). Direct ozone oxidation has been reported to be highly selective; however, ozone decomposition products such as the hydroxide radical often exhibit little substrate specificity. Decomposition products of ozone are extremely strong oxidants capable of reacting with almost any organic compound (Hoigné and Bader, 1979). The mechanism of ozone reaction was significant in that ozone could increase biodegradation of organic molecules through: (1) the direct ozone oxidation of higher order covalent bonds in organic molecules that may not be readily biodegradable; and (2) the tendency for decomposition products to oxidize and break large molecules into smaller fragments (Rice et al., 1981). Under the conditions used in aquaculture, ozone does not oxidize organic carbon all the way to carbon dioxide but breaks the organic molecule into more small molecules (Maier, 1984; Rice et al., 1981).

4.3. Nitrite

Within our system, ozonation reduced nitrite to lower concentrations in the fish culture tank water than in the water just after the LHO™ (the point where ozone was added). We think that the lower levels of nitrite within the culture tanks were caused by residual ozone (0.02–0.18 mg/l) entering the culture tanks which continued to oxidize nitrite. Although the two ozone doses evaluated within this study did show excellent reduction in nitrite (Table 1), the higher ozone dosing rate did not improve nitrite reduction within the fish culture tank with respect to the lower dosing rate.

Others have reported that ozone oxidized nitrite (Rosenthal, 1981; Sutterlin et al., 1984; Rosenthal and Kruner, 1985; Bablon et al., 1991) within recirculating aquaculture production systems. Published information on nitrite indicates that roughly stoichiometric proportions of ozone are required to oxidize nitrite to nitrate, about 1.04 mg ozone per mg nitrite (Bablon et al., 1991).

A malfunctioning biofilter generally results in accumulations of nitrite within the recirculating system; therefore, because ozone oxidizes nitrite, adding ozone to a recirculating system can somewhat protect fish from accumulations of nitrite. However, because ozone decreases the concentration of nitrite going to the biofilter, use of ozone will also cause the eventual decline in the biofilter's population of bacteria that convert nitrite into nitrate. Then, if ever ozone addition is interrupted, nitrite concentrations will rapidly accumulate to levels that can threaten fish health, because the biofilter does not have the capacity to remove all of the nitrite produced.

4.4. Turbidity

Ozonation of the recirculating system did not consistently change turbidity at any location within the recirculating system. Microflocculation produced by ozonation affects turbidity because it can change both the concentration and size of the colloids within the system (Grasso and Weber, 1988; Wilczak et al., 1992; Rueter and Johnson, 1995).

4.5. Improvements in microscreen filter performance

Adding ozone increased solids removal across the Triangel™ filter from a mean of about 24% of the feed fed to nearly 33% of the total feed fed. The 24% solids removal measured during the control was supported by previous research within the same system when ozone was not used (Heinen et al., 1996).

Ozone improved suspended solids removal across the Triangel™ filter by an average of 33% (Table 2). The improved solids removal was probably due to oxidation producing precipitation of dissolved organic molecules and microflocculation of colloidal organic solids, as first described by Maier (1984). The oxidized organic compounds are usually smaller and contain more polar compounds that are richer in oxygen and poorer in double bonds due to increased hydroxyl, carbonyl and carboxyl functional groups (Maier, 1984). Creation of the more polar functional groups can cause dissolved organics to precipitate and can also produce polyelectrolyte characteristics among the suspended particles that increase enmeshment, adsorption, and cross-linking between the solids, i.e., microflocculation (Maier, 1984).

Chang and Singer (1991) reported that the optimum ozone dosage for enhanced flocculation of organic solids was dependent upon the total organic carbon (TOC) levels and, to some extent, the relative ratio of hardness to TOC. Chang and Singer (1991) reported that a ratio of hardness to TOC of 2:5 was adequate to produce flocculation of organic material. Within our research, water hardness and TOC levels where ozone was added were about 250 mg/l and 8 mg/l, respectively, which produced a ratio of hardness to TOC more than adequate to support flocculation.

Ozonation also decreased plugging of the microscreen filter panels, as indicated by an average of 35% (range 21–48%) fewer filter wash cycles required, 53% (range 38–64%) less filter sludge flow produced, and 79% (range 53–110%) more settled solids volume in the Triangel™ filter effluents (Table 2). The decreased filter plugging was not due to ozone or ozone residuals oxidizing materials on the microscreen panel, because no ozone residual reached the microscreen filters. We can hypothesize that ozone oxidation changed the particle characteristics in a manner that reduced filter plugging, probably in part due to microflocculation increasing particle size. Also, that ozone decreased the TSS in the influents to each culture tank indicates that ozone decreased the amount of solids that typically passed through the microscreen filter (Table 1).

Solids production in our system came from three sources: uneaten feed, feces, and biofloc. The contribution of these as a percentage of daily feed fed were, respectively: $\leq 1\%$ (our estimate), about 30% (Westers, 1995), and 8–12% (Chen et al., 1991). By removing solids averaging nearly 33% of the total feed fed, ozone-enhanced microscreen filtration removed a large proportion of the net solids produced daily within the recirculating system. Additionally, the Triangel™ filters did not store the solids removed for any appreciable time (36–54 s, based upon the wash frequency), when compared to other solids separation technologies, such as granular-bed filters, settling basins, and tube or plate settlers. Storing solids within the recirculating system is undesirable because, while solids are present, the opportunity exists for nutrients to leach into the water and oxygen is consumed in biodegradation.

5. Conclusions

The results indicate that adding ozone to our recirculating system at a rate of 0.025 kg ozone per kilogram feed improved water quality, supported microscreen filtration, and, according to the data in the accompanying paper (Bullock et al., 1997), reduced bacterial gill disease associated mortalities and chemical treatments required to control BGD epizootics. Adding ozone at a higher rate (0.036–0.039 kg ozone per kilogram feed) produced similar results but was much more likely to produce fish mortality, when on occasion ozone accumulated to toxic levels (Bullock et al., 1997). Since ozonation equipment is expensive, it is rational to add ozone at the lowest effective rate necessary to achieve the desired results. Adding ozone at the lower rate is also justified to reduce potential for fish to be exposed to ozone, particularly when little hydraulic retention time is available between the fish culture tank and the ozone transfer point.

Acknowledgements

This material is based upon work supported by the United States Department of Agriculture, Agricultural Research Service under grant agreement number 59-1931-3-012. The authors appreciated editorial comments provided by Douglas Tave. Adapted with permission from *Successes and Failures in Commercial Recirculating Aquaculture*, published by NRAES, Cooperative Extension, 152 Riley-Robb Hall, Ithaca, New York 14853-5701. (607) 255-7654.

References

APHA, 1985. Standard Methods for the Examination of Water and Wastewater, 16th edn. American Public Health Association, Washington, DC, 1268 pp.

Bablon, G., Bellamy, W.D., Bourbigot, M.-M., Daniel, F.B., Doré, M., Erb, F., Gordon, G., Langlais, B., Laplanche, A., Legube, B., Martin, G., Masschelein, W.J., Pacey, G., Reckhow, D.A., Ventresque, C., 1991. Fundamental aspects. In: Langlais, B., Reckhow, D.A., Brink, D.R. (Eds.), Ozone in Water Treatment: Application and Engineering. American Water Works Association Research Foundation. Denver, CO, pp. 11–132.

Bullock, G.L., Summerfelt, S.T., Noble, A., Weber, A., Durant, M.D., Hankins, J.A., 1997. Ozonation of a recirculating rainbow trout culture system: I. Effects on bacterial gill disease and heterotrophic bacteria. Aquaculture 158, 43–55.

Chang, S., Singer, P.C., 1991. The impact of ozone on particulate stability and the removal of TOC and THM precursors. J. Am. Water Works Assn. 83 (3), 71–79.

Chen, S., Coffin, D.E., Malone, R.F., 1991. Sludge management for recirculating systems. In: Design of High-Density Recirculating Aquaculture Systems, Proceedings. Louisiana Sea Grant College Program, Baton Rouge, LA, pp. 36–43.

Chen, S., Stechey, D., Malone, R.F., 1994. Suspended solids control in recirculating aquaculture systems. In: Timmons, M.B., Losordo, T.M. (Eds.), Aquaculture Water Reuse Systems: Engineering Design and Management. Elsevier, New York, NY, pp. 61–100.

Edwards, M., Benjamin, M.M., 1991. A mechanistic study of ozone-induced particle destabilization. J. Am. Water Works Assn. 83 (6), 96–105.

Grasso, D., Weber, J.W. Jr., 1988. Ozone-induced particle destabilization. J. Am. Water Works Assn. 80 (8), 73–81.

Heinen, J.M., Hankins, J.A., Weber, A.L., Watten, B.J., 1996. A semi-closed recirculating water system for high density culture of rainbow trout. Prog. Fish-Cult. 58, 11–22.

Hirayama, K., Mizuma, H., Mizue, Y., 1988. The accumulation of dissolved organic substances in closed recirculation culture systems. Aquacult. Eng. 7, 73–87.

Hoigné, J., Bader, H., 1979. Ozonation of water: selectivity and rate of oxidation of solutes. Ozone Sci. Eng. 1, 73–86.

Liao, P.B., Mayo, R.D., 1972. Salmonid hatchery water reuse systems. Aquaculture 1, 317–335.

Maier, D., 1984. Microflocculation by ozone. In: Rice, R.G., Netzer, A. (Eds.), Handbook of Ozone Technology and Applications, Vol. 2. Butterworth, Boston, MA, pp. 123–140.

Otte, G., Rosenthal, H., 1979. Management of a closed brackish water system for high density fish culture by biological and chemical treatment. Aquaculture 18, 169–181.

Otte, G., Hilge, V., Rosenthal, H., 1977. Effect of ozone on yellow substances accumulated in a recycle system for fish culture. International Council for the Exploration of the Sea, Fisheries Improvement Committee, Copenhagen, C.M. 1977/E:27: 1–13.

Paller, M.H., Lewis, W.M., 1988. Use of ozone and fluidized-bed biofilters for increased ammonia removal and fish loading rates. Prog. Fish-Cult. 50, 141–147.

Poston, H., Williams, R.C., 1988. Interrelations of oxygen concentration, fish density, and performance of Atlantic salmon in an ozonated water reuse system. Prog. Fish-Cult. 50, 69–76.

Reid, B., Arnold, C.R., 1992. The intensive culture of penaeid shrimp *Penaeus vannamei* Boone in a recirculating raceway system. J. World Aquacult. Soc. 23, 146–153.

Rice, R.G., Robson, C.M., Miller, G.W., Hill, A.G., 1981. Uses of ozone in drinking water treatment. J. Am. Water Works Assn. 73, 1–44.

Rosenthal, H., 1981. Ozonation and sterilization. In: Tiews, K. (Ed.), Proceedings of World Symposium on Aquaculture in Heated Effluents and Recirculation Systems, Vol. I. Heenemann Verlagsgesellschaft, Berlin, Germany, pp. 219–274.

Rosenthal, H., Kruner, G., 1985. Treatment efficiency of an improved ozonation unit applied to fish culture situations. Ozone: Sci. Eng. 7 (3), 179–190.

Rosenthal, H., Otte, G., 1980. Ozonation in an intensive fish culture recycling system. Ozone: Sci. Eng. 1, 319–327.

Rueter, J., Johnson, R., 1995. The use of ozone to improve solids removal during disinfection. Aquacult. Eng. 14, 123–141.

Sander, E., Rosenthal, H., 1975. Application of ozone in water treatment for home aquaria, public aquaria, and for aquaculture purposes. In: Blogoslawski, W.J., Rice, R.G. (Eds.), Aquatic Applications of Ozone. International Ozone Institute, Stamford, CT, pp. 103–114.

Staehelin, J., Hoigne, J., 1985. Decomposition of ozone in water in the presence of organic solutes acting as promoters and inhibitors of radical chain reaction. Environ. Sci. Tech. 19, 1206–1213.

Summerfelt, S.T., Hankins, J.A., Summerfelt, S.R., 1993. Modeling continuous culture with periodic stocking and selective harveting to measure the effect on productivity and biomass capacity of fish culture systems. In: Wang, J.K. (Ed.), Techniques for Modern Aquaculture. American Society of Agricultural Engineers, Saint Joseph, MI, pp. 581–595.

Summerfelt, S.T., Hankins, J.A., Heinen, J.M., Weber, A.L., Morton, J.D., 1994. Evaluation of the Triangel™ microsieve filter in a water-reuse system. In: World Aquaculture 1994 Book of Abstracts. World Aquaculture Society, Baton Rouge, LA, p. 45.

Sutterlin, A.M., Couturier, C.Y., Devereaux, T., 1984. A recirculation system using ozone for the culture of Atlantic salmon. Prog. Fish-Cult. 46, 239–244.

Westers, H., 1995. Feed and feeding strategies to reduce aquaculture waste. In: Timmons, M.B. (Ed.), Aquacultural Engineering and Waste Management. Northeast Regional Agricultural Engineering Service, Ithaca, NY, pp. 365–376.

Wilczak, A., Howe, E.W., Aieta, E.M., Lee, R.G., 1992. How preoxidation affects particle removal during clarification and filtration. J. Am. Water Works Assn. 84 (12), 85–94.

Williams, R.C., Hughes, S.G., Rumsey, G.L., 1982. Use of ozone in a water reuse system for salmonids. Prog. Fish-Cult. 44, 102–105.